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AGE AND GROWTH STUDY OF THE JACK MACKEREL (*Trachurus japonicus*) IN THE NORTHEATERN WATERS OFF TAIWAN

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Key words: jack mackerel (*Trachurus japonicus*), otolith, age and growth.

ABSTRACT

Jack mackerel (*Trachurus japonicus*) is one of the most important fish resources in the northeastern Taiwan. Because of the flourishing of Taiwanese seiner fisheries in recent years, the proportion and catch of jack mackerels have increased. However, the studies on their age and growth are outdated, thus data on the catch-at-age composition are lacking. The present study collected jack mackerel otolith samples from May, 2010, to April, 2011, for age determination and combined those data with length and weight data from 2005 to January, 2012, to investigate the catch-at-age of jack mackerel in the northeastern waters off Taiwan. The regression equations for fork length (FL) and body weight (BW) of jack mackerel were significantly different between females and males ($p < 0.05$). The equations were $BW = 3.6 \times 10^{-2} \times FL^{2.6771}$ for females and $BW = 3.2 \times 10^{-2} \times FL^{2.7108}$ for males. The formation of opaque zones was used as the standard for ring calculation. Ring formation occurred once every year during January and February regardless of sex. The obtained ages and corresponding FL data were introduced into the von Bertalanffy growth function showing that the maximum FL was 40.4 cm with growth coefficient of 0.223 yr^{-1}. The jack mackerel catch in the northeastern waters off Taiwan were the age-0 (39%) and age-1 (38%), with high proportion of immature fish.

I. INTRODUCTION

Jack mackerel (*Trachurus japonicus*) is a fish species with a narrow distribution area, specifically the northwestern Pacific Ocean waters off Taiwan, and the coastal waters surrounding China, Japan, and the Korean Peninsula. There are 22 genera and 54 species of Carangidae in the waters off Taiwan, but there is only one *Trachurus* genus found in Taiwan [16]. The ecological habits of jack mackerel are swimming in schools in coastal waters, a diel vertical distribution and a diet of copepods (Copepoda), larvae, and small crustaceans [34].

Mackerel and carangid fishery is the largest coastal fishery in northeastern Taiwan, and the catches are primarily blue mackerel (*Scomber australasicus*), chub mackerel (*Scomber japonicas*), jack mackerel (*Trachurus japonicus*), brown-striped mackerel (*Decapterus maruadsi*), shortfin scad (*Decapterus macrosoma*), and redtail scad (*Decapterus kurroides*). The catch of jack mackerels is the highest among the Carangidae, accounting for more than 40% of the Carangidae caught. The annual catch statistics of Taiwan officially separated jack mackerels from Carangidae to perform independent itemized statistics. The average catch of jack mackerel between 1989 and 1994 was only approximately 300 tons. The catch of jack mackerel gradually increased from 1995 and reached 7,942 tons in 2003; currently, the annual catch is maintained at the level of 5,000 tons. The fishing methods for jack mackerel include the Japanese seine, Taiwanese seine, trawler, set net, pair seine, gill net, pole and line, and long line. The Taiwanese seine has gradually flourished in recent years, and its catch reached 40,000 tons in 2008; therefore, the Taiwanese seine has gradually replaced the large purse seine (Japanese seine) [18]. Because the Taiwanese seine has the advantages of higher agility, vessel miniaturization, and rapid operation and requires fewer labor resources, the boats increased from 2 in 2001 to 34 to 2010. The catch of jack mackerel exhibits an increasing trend, and its proportion in the catch is five times higher than in the Japanese seine [37]. Because jack mackerel resources are increasingly important, management and resource assessment of this species demand immediate actions.

Studies in Japan have shown that jack mackerel is divided into the Pacific Ocean group and the Tsushima warm current stocks. The latter extends from Japanese waters to the southern East China Sea (ECS), which is closely associated with Taiwan. There are many studies on the reproduction and ecology of jack mackerel in Japan. The related studies note

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that the depth of the spawning ground of jack mackerel is 100-200 m, the suitable water temperature for the spawning parent fish is 15-25°C, and the suitable hatching temperature is 18-24°C [25, 41]. During the spawning seasons, the spawning ground of the peak period during January and March is in the southwest (west of 125°E longitude and south of 30°N latitude) and central (30°N latitude) ECS. The spawning ground then gradually moves northward to the northwest waters off Kyushu and the surrounding waters of Tsushima during April and May and to the southern waters off South Korea during July and August [9]. However, some scholars also note that the earliest spawning ground is approximately 28° north latitude in the ECS [30, 31]. For age and growth, many scholars use age characters such as otolith, scale, and urohyal to understand the growth characteristics of jack mackerels [15, 19, 21-23]. The study of Nakajima (1982) [22] noted that the fork length of age-1 jack mackerels of the northern Kyushu was 16.6 cm and the fork length of age-2 jack mackerels was 23.1 cm; the report of Nishida and Hasegawa (1994) [23] noted that the fork length of age-4 jack mackerels in the eastern Sea of Japan was comparable to the fork length of age-3 jack mackerels in the central ECS and northern Kyushu, indicating that different areas cause changes in the growth of jack mackerels.

Taiwan is located in the southernmost end of the spawning ground of jack mackerels. Some scholars have proposed that larval jack mackerels are transported through Kuroshio to the western Pacific Ocean and the waters surrounding Kyushu, Japan [14, 30]. However, there is no conclusive evidence showing that the jack mackerels around Taiwan belong to the same stock in the Tsushima warm current and/or the western Pacific Ocean. The jack mackerel resource condition in the northeastern waters off Taiwan is very important, but studies about jack mackerels are quite rare. In studies of their reproductive period, Lin (1994) [16] collected jack mackerel samples of trawler catches from Da-xi and Yi-lan to study their parasites and speculated that the period of greatest gonad maturity occurred when they were 2 or 3 months old. Wu (2010) [39] used a gonadosomatic index (GSI) and gonadal section observations to estimate that the peak spawning period of jack mackerels was at the age of 3-5 months and the mature fork length was 18.9 cm. In related studies on their age and growth, only Yang (1960) [40] collected scales from 40 jack mackerel samples from fish markets in Keelung to perform age and growth studies and obtained the growth equation of $FL = 41.8[1-e^{-0.265(t+1.557)}]$. Therefore, studies on jack mackerels have been insufficient, especially from the age and growth perspective. The existing growth parameters in the literature are outdated, and the sample size is too small. Thus, it is necessary to investigate the current growth characteristics of jack mackerels using different characters to establish a growth equation that is suitable for the current resource status.

An otolith is a crystal formed by biomineralization; its main components are calcium carbonate, organic substances, and trace elements [8, 36, 43]. Most cartilaginous fish have three pairs of otoliths, the sagittae, lapilli, and asterisci. The growth rate of these three pairs of otoliths changes when the developmental stage changes. The sagittae are the largest (Pannella, 1971) and are easy to be observed; therefore, they are usually used for age determination in fish [5, 28]. Jack mackerel otoliths exhibit a long oval shape; the rostrum is obvious, and the sulcus extends to the ventral side. Most studies on age determination usually employ scales and otoliths. Because otoliths have the advantages of continuous growth and are less likely to be reabsorbed by fish, they have been used by an increasing number of scholars [6, 13].

Jack mackerel is an important fish resource in Japan, South Korea, and China. Japan has the largest production of jack mackerels since 1950; the maximum production was 527,000 tons, and the annual average is 236,000 tons. The catch in 2007 in China also reached 186,000 tons; thus, the economic value of jack mackerel cannot be underestimated. The northern waters off Taiwan may also be the southernmost spawning ground for jack mackerel [41], the ecological status of this area cannot be ignored. The increasing development of the Taiwanese seine in recent years has increased the catch and proportion of jack mackerel. Therefore, it is urgent to perform in-depth studies on this species. However, the reports on age and growth in Taiwan are outdated; thus, data on the catch-at-age composition are lacking. Therefore, the present study investigated the age and growth characteristics of jack mackerel to assist resource assessment and the management of jack mackerel populations. The purposes of the present study were as follows: (1) use the otolith rings to estimate the age and growth of jack mackerels; and (2) estimate the catch-at-age composition of jack mackerel in Taiwanese seine and trawler catches.

II. MATERIALS AND METHOD

1. Data Source and Biological Experiments

During May, 2010, and January, 2012, jack mackerel samples from Taiwanese seine and trawler catches in the northeastern waters off Taiwan were collected once or twice each month in the Ba-dou-zi Fishing Harbor of Keelung and the Ao-di Fishing harbor and the Da-xi Harbor of Yi-lan. A total of 423 jack mackerel otolith samples were collected, including 227 female samples and 205 male samples. In addition, the fork lengths and body weights of the jack mackerels during December, 2005, and April, 2007, and during March, 2009, and April, 2010, were measured, which included 6,709 samples from Taiwanese seine catches and 4,045 samples from trawler catches, with a total of 10,754 samples.

1) Preliminary Processing of Samples and Basic Measurement

The samples were brought back to the laboratory after collection. The fork length (FL) and body weight (BW) were measured to an accuracy of 0.1 cm and 1 g, respectively, and the gender of the samples was determined. The samples were numbered, and the results were recorded accordingly. After measurement, the bone above the fish's heads was cut off, and

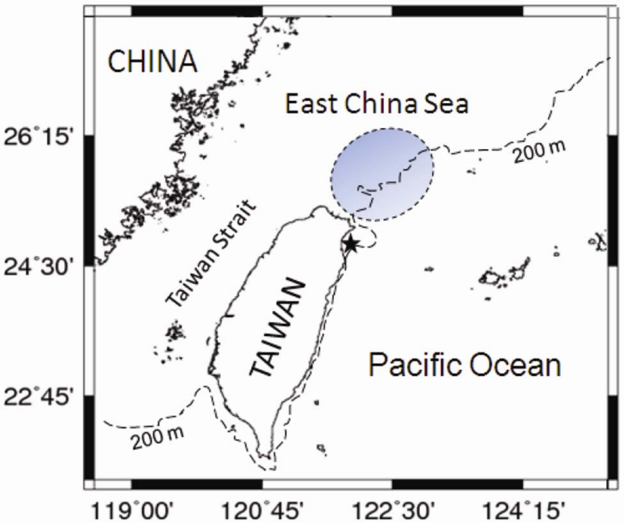

Fig. 1. The location of the collection of jack mackerel samples (shaded area: Taiwanese seine sampling area; asterisk: trawler sampling area).

the pair of sagittae was removed using forceps (Fig. 1). After the attached tissues were removed, the sample was placed in a plastic tube containing deionized water to soften and detach the remaining tissues for subsequent otolith treatment.

2) Otolith Sample Treatment and Observation

- Cleaning

All otoliths were washed and cleaned using deionized water and baked in a 50°C oven for 5-6 hours to ensure that they contained no residual water. If there was any tissue on the surface of otoliths, the otoliths were then washed with 5% H_2O_2, followed by rinsing with deionized water to remove any residual H_2O_2.

- Embedding

After drying, the left otolith was uniformly used for experiments. The otolith weight (OW) was measured to an accuracy of 0.001 g; the appearance of the otolith was vertically photographed using a camera (Canon 50D, Japan) with a stand. The otolith length (OL) was then measured using Image J imaging analysis software (Fig. 2). After the data were recorded, the groove of the embedding board was filled with embedding medium composed of thoroughly mixed epoxy (Epofix kit, Strues) and hardener (25:3 w/w), and then the otolith was placed on the bottom of the groove of the embedding board with the internal face of the otolith facing downward. The bubbles in the embedding medium were removed using forceps to prevent interference in the subsequent observation. Finally, the embedding board was incubated at room temperature for 1-2 days until the epoxy hardened. After confirming that the sample had dried, the sample was placed in a plastic box according its labeling number for subsequent experiments.

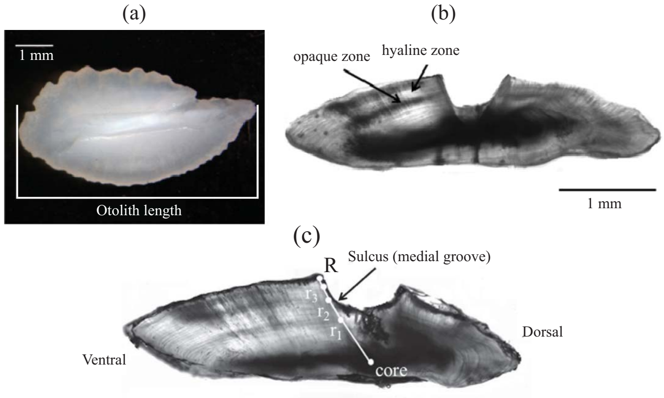

Fig. 2. The measurement of (a) the otolith length, (b) the hyaline zone and opaque zone of an otolith section, and (c) the otolith radius of jack mackerels.

- Sectioning and grinding

The otolith core was first labeled, and a slow-speed cutting machine (Buehler isomet low speed saw) was used to cut a 0.5~1 mm transverse plane. The obtained sections were used for the second embedding to increase the thickness and facilitate the grinding operation. Next, the sample was placed on a flat-disc grinder-polisher (Metaserv grinder-polisher, Buehler) and ground using P1200 and P2400 water sandpapers; the grinding was observed using a microscope until the light and dark bands of the rings could be clearly discriminated. The surface of the sample was then polished using flannel and 0.05 μm Al_2O_3 to eliminate scratches caused by grinding and to make the interpretation smoother.

- Observation

The appearance of the otoliths was photographed using a microscope (Olympus BX-51, Japan) connected to an external camera (Canon G12, Japan). The photos were stored and the otolith radius was measured using imaging analysis and processing software. To ensure the accuracy of the ring interpretation, one otolith sample was judged by three ring interpreters; the dark band (opaque zone) was used as the standard for the ring marks (Fig. 2). If the results of the ring interpretation by more than two people were the same, then the sample was used. The same number of rings from more than two interpreters was used as the number of rings. If the ring interpretation results of the three people were different then the sample was discarded [1, 33]. For the measurement of otolith radius, there were clearer and visible rings along the ventral side of the sulcus of the otolith sections of jack mackerels (Anderson *et al*., 1992). Thus, those rings were the best ring axis for the measurements in this study. The measurement from the otolith core to the inner edge of the dark band of the first ring was r_1, the measurement from the core to the inner edge of the dark band of the second ring was r_2, and so on; the measurement from the otolith core to the very outer edge was R (Fig. 2).

2. Data Analysis and Parameter Calculation

1) Regression Relationship between Lengths and Weight of Fish and Otoliths

The present study analyzed 10,754 jack mackerel samples including 3,286 female samples, 2,328 male samples, and 5,140 samples of unknown gender or without examining the gonads. The regression equation was obtained using the actual measurement results of the fork length and body weight. The difference between females and males was then examined using the maximum likelihood ratio; if there was a significant difference, the data for the female and male samples were processed separately, otherwise the data were processed together. A simple linear regression was also performed on fork length and otolith length and weight. The differences in fork length, otolith length, and otolith weight between females and males were examined using analysis of covariance (ANCOVA) and the method of maximum likelihood.

2) Error Analysis of Rings

The results of the ring interpretations of the usable samples were used to calculate the degree of error of a single sample after repeated ring interpretations. This study used an index of average percentage error (IAPE) and a coefficient of variation (CV) to analyze the degree of accuracy of the ring interpretation results [2].

3) Formation Period of Rings

In addition to investigating the number of rings, the number of rings that were formed each year in the samples was also investigated. This study used the marginal increment ratio (MIR) to analyze the period of ring formation [22, 27, 35] and used the calculated MIR of the samples in each month to analyze the monthly variations.

4) Estimation of Parameters of the Growth Equation

A growth equation is used to represent the condition of changes in age and body length of organisms over time. The von Bertalanffy growth function (VBGF), which is often used in the study of the growth of bony fish, was used in this study to investigate the growth curve of jack mackerels. The ages and corresponding fork lengths were introduced into the VBGF followed by a nonlinear regression analysis using the SAS statistical software to obtain the parameters of the growth equation.

III. PROCESSING TECHNIQUES

1. Relationship Equation between Fork Length and Body Weight

The female-to-male ratio in the samples collected in this study was 1.4:1. The regression relationship of fork length and body weight between female and male fish was analyzed, and results of the maximum likelihood method showed that there was a significant difference between female and male

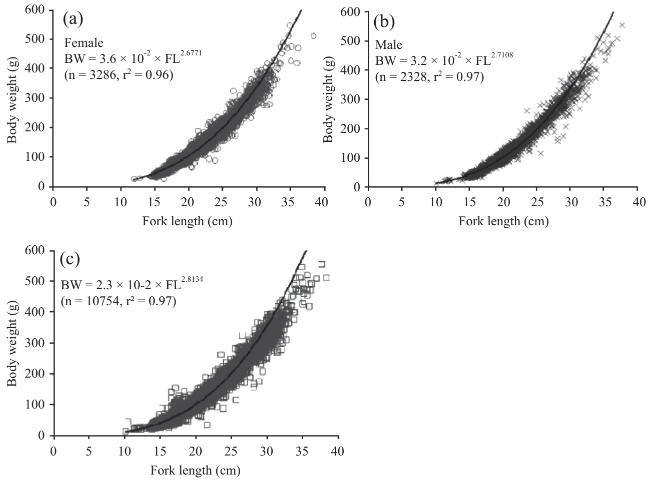

Fig. 3. The regression relationship between fork length and body weight of jack mackerels for (a) females, (b) males, and (c) combined.

fish ($p < 0.05$); therefore, the data for the different genders were processed separately. The following relationship equations between fork length and body weight were obtained:

Female fish:
$$BW = 3.6 \times 10^{-2} \times FL^{2.6771} \text{ } (n = 3{,}286, r^2 = 0.96) \text{ (Fig. 3(a))} \quad (1)$$

Male fish:
$$BW = 3.2 \times 10^{-2} \times FL^{2.7108} \text{ } (n = 2{,}328, r^2 = 0.97) \text{ (Fig. 3(b))} \quad (2)$$

Because samples with unknown genders accounted for nearly 50% of the total samples, the relationship equation when all individual data were combined was also obtained:

$$BW = 2.3 \times 10^{-2} \times FL^{2.8134} \text{ } (n = 10{,}754, r^2 = 0.97) \text{ (Fig.3(c))} \quad (3)$$

2. Relationship Equation between Fork Length and Otolith Length and Weight

The analysis of the linear regression relationship between the fork length and otolith length of jack mackerels was analyzed in this study, and the relationship equations for the female and male fish are shown below:

$$\text{Female fish: } OL = 0.2504FL^{2.2731} \text{ } (n = 260, r^2 = 0.85) \quad (4)$$

$$\text{Male fish: } OL = 0.2305\, FL^{2.7358} \text{ } (n = 201, r^2 = 0.88) \quad (5)$$

The ANCOVA results showed that there was no significant difference between female and male fish ($p > 0.05$); therefore, all data were combined for processing. The regression equation was as follows:

$$OL = 0.2425\, FL^{2.449} \text{ } (n = 432, r^2 = 0.88) \quad (6)$$

Table 1. The relationship between the distribution of rings and fork lengths.

FL (cm)	number of ring mark					
	0	1	2	3	4	5
14	6					
15	20					
16	18	1				
17	9	2	1			
18	1	16	2			
19	1	21	12			
20		16	19			
21		9	11			
22		2	22			
23		3	23	3		
24			18	10		
25			14	14		
26			5	17	1	
27				13	4	
28				16	6	
29				2	15	
30				3	12	
31				3	8	
32					2	1
n	55	70	127	81	48	1
Mean	16.0945	19.79	22.5654	26.8383	29.7896	32.2
SD	1.0802	1.39462	2.11999	1.88809	1.33914	

The fork length and otolith weight showed an exponential correlation. The results of the maximum likelihood method showed that there was a significant difference between female and male fish ($p < 0.05$). The equations are shown below:

Female fish: $OW = 3 \times 10^{-5} \times FL^{2.2546}$ ($n = 227$, $r^2 = 0.89$) (7)

Male fish: $OW = 5 \times 10^{-5} \times FL^{2.0942}$ ($n = 205$, $r^2 = 0.91$) (8)

Otolith length and weight both had a positive correlation with fork length, indicating that otoliths grow with the growth of fish; therefore, the growth of jack mackerels can be investigated through otoliths.

3. Analysis of Ring Interpretation

The present study collected 432 otolith samples for ring interpretation. Among the samples, 28 samples could not be properly interpreted due to improper treatment of the samples (6.5%); 22 samples were also discarded because the ring numbers from three interpretations were different (5.4%). Finally, 382 samples were successfully interpreted, which accounted for 88.4% of the samples. The IAPE was 4.8%, and the CV was 6.6%. The formation of opaque zones was used as the standard for ring calculation in the present study. The maximum ring number in the ring interpretation for female fish was 4 (FL = 32.0 cm), and the minimum was 0 (FL = 14.7 cm); the maximum ring number for male fish was 5 (FL = 32.4 cm), and the minimum was 0 (FL = 14.3 cm). The average fork lengths of fish with 0 to 5 rings were 16.1 cm, 19.8 cm, 22.6 cm, 26.8 cm, 29.8 cm, and 32.2 cm, respectively (Table 1).

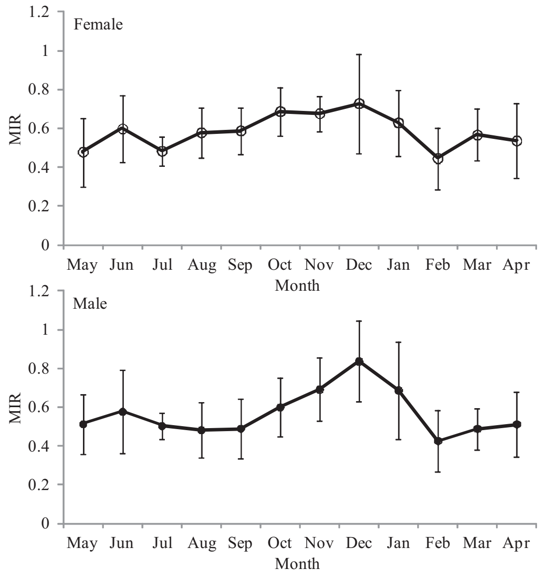

Fig. 4. The monthly variation of the marginal increment rate (MIR) of jack mackerel

4. Analysis of Marginal Increment and Estimation of Age

Fig. 4(a) shows the trend of monthly variation of *MIR* of female jack mackerels, which increased from 0.48 in May to a high value of 0.73 in December and then fell to a low point of 0.44 in February of the next year before gradually increasing afterwards. The marginal increment rates were closest to 0 in February regardless sex (Fig. 4(b)).

Thus, it was estimated that a new ring was going to form at this time, and the cycle was once per year. To estimate the ages of the actual samples, the ring formation cycle, ring interpretation data, hatched date, and sample collection time were all considered. According to the study of Wu (2010), the peak spawning period of jack mackerels in the northeastern waters off Taiwan is from March to May. The present study set the hatched date of jack mackerels as March 1st; thus, the actual age of the first ring would be 0.91 (11 months). In addition, the duration between the formation of the last ring and the capture time would also be considered; for example, if a sample was captured in August, then the age of this sample would be the observed ring age plus 0.5 (6 months).

5. Growth Equation

The obtained ages and corresponding fork length data were introduced into the growth equation to obtain the growth equations of females and males:

Female fish: $L_t = 39.2181[1-e^{-0.2351(t+1.5927)}]$ ($n = 191$) (Fig. 5(a)) (9)

Table 2. Estimation of relative fork lengths corresponding to ages using the von Bertalanffy growth function.

Age (year)	FL (cm)	Growth rate (cm/year)
1	17.92	
2	22.41	4.48
3	26.00	3.59
4	28.87	2.87
5	31.17	2.30
6	33.01	1.84
7	34.49	1.47
8	35.67	1.18
9	36.61	0.94
10	37.37	0.76

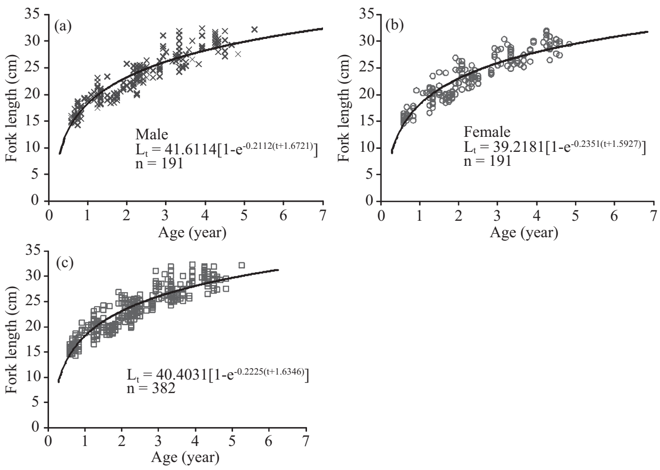

Fig. 5. The von Bertalanffy growth function for male jack mackerels.

Male fish: $L_t = 41.6114[1-e^{-0.2112(t+1.6721)}]$ (n = 191) (Fig. 5(b)) (10)

Examination using the maximum likelihood method showed that there was no significant difference between female and male fish ($p > 0.05$); therefore, all data were combined to obtain the following equation:

$$L_t = 40.4031[1-e^{-0.2225(t+1.6346)}] \text{ (n = 382) (Fig. 5(c))} \quad (11)$$

The above Eq. (11) was used to estimate the fork length at each age and yearly average growth rates as shown in Table 2. The results showed that the fork lengths of age-1, age-2, and age-5 jack mackerels were 17.9 cm, 22.4 cm, and 31.1 cm, respectively. The growth rate in the first year after hatching was 4.48 cm/year, in the second year it was 3.59 cm/year, and it gradually decreased to 2.30 cm/year in the 5th year.

6. Catch-at-Age Composition

Table 3 showed the analysis estimating the catch-at-age composition in the Taiwanese seine and trawler catches. The jack mackerels in the Taiwanese seine catches were mainly

Table 3. Catch-at-age compositions of Taiwanese seine and trawler catches during December, 2005, and January, 2012. (TS = Taiwanese seine; TL = Trawler)

Year	Fishing Gear	Proportion (%)			
		age-0	age-1	age-2	age-3+
2005 (Dec)	TS	-	-	-	-
	TL	32	0	62	6
2006 (Jan-Dec)	TS	-	-	-	-
	TL	33	13	7	47
2007 (Jan-Apr)	TS	-	-	-	-
	TL	17	19	9	55
2009 (Mar-Dec)	TS	28	47	18	7
	TL	-	-	-	-
2010 (Jan-Dec)	TS	47	37	8	7
	TL	72	7	7	14
2011 (Jan-Dec)	TS	31	53	13	3
	TL	33	37	20	10
2012 (Jan)	TS	4	82	14	0
	TL	4	87	8	1

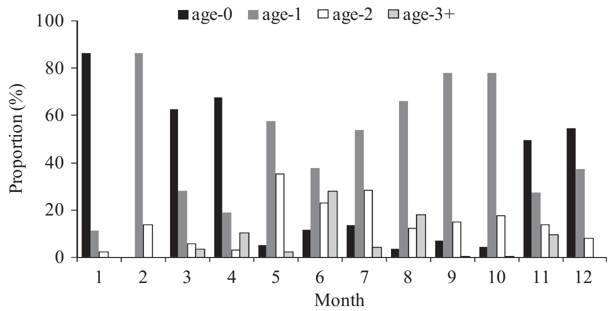

Fig. 6. Monthly catch-at-age compositions of jack mackerels in Taiwanese seine catches between 2009 and 2011.

age-1 fish, which accounted for 44%; while age-0 fish accounted for 37%. The trawler catches were mainly age-0 fish, which accounted for 43%, while age-1 fish accounted for 26%. The proportions of age-2 fish in the Taiwanese seine and trawler catches were 18% and 30%, respectively. When the monthly data were analyzed, there were a large amount of age-0 fish captured in Taiwanese seine catches between November and April (Fig. 6), while there were more age-1 fish between May and October, and there was a high proportion of age-2 and above jack mackerels captured between May and July. When the yearly data were analyzed, there was a higher proportion of age-0 fish in 2010, which accounted for 46%, but there was a higher proportion of age-1 fish in 2011, which accounted for 52% (Fig. 7). The monthly catch-at-age composition in the trawler catches showed that there was a higher proportion of age-0 fish in the catches between October and March, and there was a higher proportion of age-1 and age-2 fish between April and August (Fig. 8). The comparison of the catch-at-age data of jack mackerel in trawler catches between

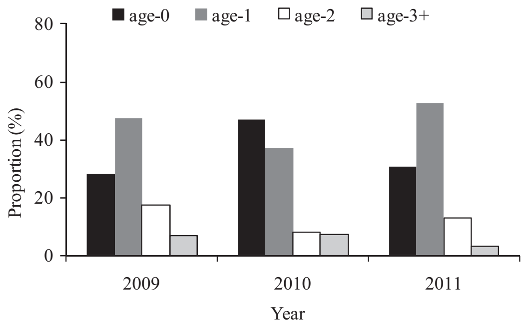

Fig. 7. Variations in catch-at-age for jack mackerels in Taiwanese seine catches between 2009 and 2011.

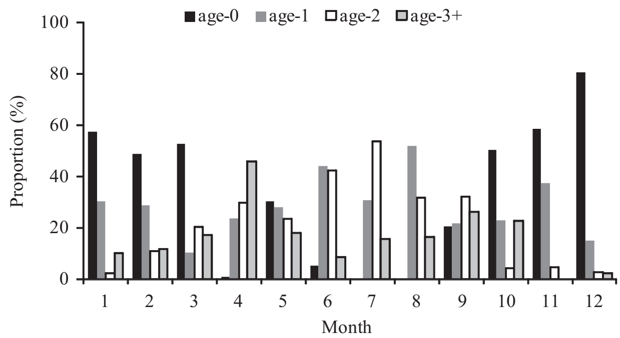

Fig. 8. Monthly catch-at-age compositions of jack mackerels in trawler catches between May, 2010, and January, 2012.

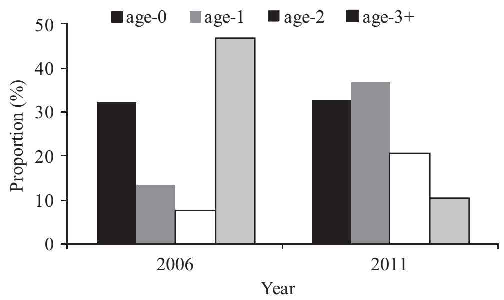

Fig. 9. Catch-at-age compositions of jack mackerel in trawler catches in 2006 and 2011.

2006 and 2011 showed that the proportion of age-3 fish decreased significantly (Fig. 9).

IV. DISCUSSION AND CONCLUSIION

1. Formation of Otolith Rings and Age Determination

To understand the errors in the interpretation of the results, the statistical results in the literature [6] from 131 reports showed that approximately 50% of studies used the combined average percentage error index and coefficient of variation together for the accuracy index of the age variable. These reports also considered that an index and coefficient lower than 5.5% and 7.6%, respectively, was acceptable. In this study, the average percentage error index of ring determination was 4.8%, and the coefficient of variation was 6.6% in the present study, both of which were within the acceptable range.

Generally, there are several necessary conditions for the age variable. For example, the increase in the variable should be positively correlated with the growth of the fish [11, 39]. The ring variable should increase with the growth of the fish, and the formation of ring should be periodic [10]. The results in the present study showed that both the length and weight of the otoliths of jack mackerels were positively correlated with fork length, and the rings were formed in a regular circle (Figs. 5 and 6). Therefore, otoliths can be used to determine age for jack mackerels. For the formation of otolith rings, scholars have speculated that it might be associated with factors such as water temperature, feeding, reproduction, light exposure, metabolism, endocrine, and the environment [3, 20]. Ring formation in jack mackerel otoliths was first observed by Imaoka (1967) [12]. He observed the formation time of the hyaline and opaque zones in the sagittal plane of otoliths of jack mackerels from the western waters off Japan and found that the samples with opaque zones at the most outer edge of the otoliths were concentrated between February and April, which was similar to the reproductive period of jack mackerels. According to the reports of Lin (1994) [16] and Wu (2010) [37], the reproductive period of jack mackerels in the northeastern waters off Taiwan is during January and May, which was also the ring formation period found in the present study (Fig. 4). Observation of the ring radius of immature jack mackerels (age-0 fish) also showed that the radius was also smaller during January and March.

The monthly variation of the marginal increment rates was used to observe the frequency of otolith ring formation. However, samples from old fish might be difficult to interpret because the outer rings were too dense [6]. The samples in the present study were younger than 5 years old. Therefore, the rings were easy to identify, and the chance of producing errors was small. Using otoliths of jack mackerels as a variable showed that one ring was formed each year; which was consistent with the results in the present study [22, 23]. The results in the present study showed that the value of marginal increment rate was the lowest in February; therefore, the ring formation period was consistently set on March 1st.

2. Age and Growth Parameters

The present study used the von Bertalanffy growth equation to show that the maximum fork length was 40.4 cm and the growth coefficient was 0.223 yr^{-1}. The maximum fork length was close to the largest fork length (38.3 cm) observed in the samples, indicating that the sampling error was small and the estimated parameters were reliable. Using the equation to estimate maximum age proposed by Taylor (1958) [35], the maximum age of jack mackerels in the present study was 11.7 years, which was close to the report by Novikov *et al*. (2002) [24] showing that the maximum age of jack mackerels was 12 years. With respect to the growth coefficient, Branstetter

Table 4. Comparison of growth equation parameters of jack mackerels in this study and related studies.

Authors	Study Area	L_∞	K	T_0
This study	Northern Waters off Taiwan	40.4	0.22	-1.63
Yang (1960 [40]	Waters off Taiwan	41.8	0.27	-1.56
Mitani and Ida (1964) [19]	Northern East China Sea	35.4	0.73	-0.07
	Japan Sea (northern Kyushu)	38.6	0.35	-0.60
Nakashima (1982) [22]	Central East China Sea	40.4	0.31	-0.75
	Southern West China Sea	32.5	0.26	-1.47
Nishida and Hasegawa (1994) [23]	Japan Sea (Niigata)	38.1	0.28	-0.73

(1987) [4] made the following classification: a growth coefficient between 0.05-0.10 yr^{-1} indicates a slow-growing species, between 0.10-0.20 yr^{-1} indicates a normal-growing species, and between 0.20-0.50 yr^{-1} indicates a fast-growing species. Jack mackerel and brown-striped mackerel [27], shortfin scad, and mackerel scad (*Decapterus macarellus*) [33] in adjacent waters are all fast-growing species.

The same species of fish habitating in different habitats (water temperature, nutrient salts, baits, etc.) will cause differences in the characteristics of reproduction and growth [7, 19, 42]. Table 4 shows the comparison of the growth parameters between jack mackerels in the present study area and in other waters. The parameter estimation results in studies using scales as the variable had large differences compared with other studies [19], and the growth coefficient might be overestimated. Other scholars have estimated that the maximum fork length is between 32.5-41.8 cm and the growth coefficient is between 0.27-0.38 yr^{-1}. Comparison of the growth coefficients in the present study with other studies showed that the growth of jack mackerels in Japanese waters was faster. In Japanese waters, the sea water temperature is lower, the basic productivity is higher, and the diets are richer; which may promote faster growth. In addition, the impact of fishing may also cause environmental changes that change the growth patterns of fish species [29].

3. Catch-at-Age Composition and Fisheries Management

Different fishing methods in the northeastern waters off Taiwan had different catch-at-age compositions of jack mackerel. The proportion of jack mackerel in trawler catches was 2.6 times the proportion in Taiwanese seine catches (Figs. 8 and 9). One possible reason is that the operational depth of a trawler is deeper than for a Taiwanese seine. According to the study by Liu (2006) [17], the proportions of jack mackerel and blue mackerel in deep waters are larger than in shallow waters. Overall, the fork lengths of jack mackerels in the samples of the present study showed that age-0 fish accounted for 39% of the total sample in the catch from the northeastern waters off Taiwan. On the other hand, the center of distribution of age-0 jack mackerels in the ECS in winter moves southward because the edge of the continental shelf in the ECS is warmer and has better food conditions in winter [32, 38]. The present study also found that the proportion of age-0 fish was particularly high at the transition between winter and spring (Table 5), indicating that the northeastern waters off Taiwan were the breeding field for larval jack mackerels in winter. Further study is needed to confirm whether jack mackerels in this area really swim northward and finally join the Tsushima warm current group in Japan or if jack mackerels in this area belong to other stock groups because their age and growth characteristics are different from those in Japanese waters.

Table 5. Monthly catch-at-age compositions between March, 2009, and January, 2012.

Month	Proportion (%)			
	age-0	age-1	age-2	age-3+
1	77	17	2	3
2	42	37	11	10
3	61	25	9	6
4	58	20	7	15
5	16	45	30	9
6	8	41	32	19
7	10	48	35	7
8	3	63	16	18
9	8	74	16	2
10	22	56	12	9
11	53	32	10	5
12	68	26	5	1

The report of Ohshimo *et al*. (2004) [26] noted that the utilization of the jack mackerel resource in the Tsushima warm current group in Japan before 1945 was in the early development stage, and the catches of jack mackerels in the ECS and Japanese waters were mostly below 10,000 tons. The period between 1946 and 1966 was the development stage because of the development of new fishing grounds and the rise of the Japanese seine, and the fishing catches increased greatly. The period between 1967 and 1980 was a recession period because of the high impacts of fishing: the parent stock decreased, the amount of recruitment decreased, and the jack mackerel catches decreased. After 1982, the resources gradually recovered, leading to the restoration period. The Japanese seine catches account for 80% of jack mackerel catches in Japan, and the average number of catches is between 2,000 and 3,000 million. The catch-at-age composition is mainly age-0 and age-1 fish, and the proportion of fish above 3 years old is low. The average catches before 1994 in Taiwan were below 700 tons; after 1995, catches greatly increased, possibly due to the increasing use of the Taiwanese seine. The Taiwanese seine catches accounted for nearly 70% of jack mackerel catches, and the average number of fish in each catch was approximately 30 million. The catch-at-age composition was the same as in Japan, with most fish being age-0 and age-1. However, the proportion of fish older than 3 years old was higher in Japan. Using the report of Wu (2010) [37] to estimate the fork length of jack mackerels at 50% sex maturity in the waters of the present study showed that the fork length was 18.9 cm, and the estimation using the growth equation in the present study showed that the fish should have been 1.2 years old. Therefore, it was estimated that over 35% of jack mackerels were captured before maturation. The high proportion of age-0 fish in the catches will have a negative impact on the amount of recruitment and close supervision is needed in the future. Furthermore, in addition to jack mackerels, the catch compositions of mackerel and carangid fisheries in the northeastern waters off Taiwan are mainly blue mackerel, chub mackerel, brown-striped mackerel, shortfin scad, and redtail scad. There are various fish species in these catches; thus, it is difficult to manage one single fish species. Because there are high proportions of blue mackerel and jack mackerel, these two species should be used as indicators for mackerel and carangid fisheries management.

4. Conclusion

The present study used otolith samples of jack mackerels as the variable for age determination and used cross-sections to interpret the rings and formation cycles. The rings were formed once every year during January and February, and the formation period of the ring was associated with the reproductive period. Using the von Bertalanffy growth function, it was estimated that the maximum FL was 40.4 cm and the growth coefficient was 0.223 yr^{-1}; the growth of jack mackerels in the northeastern waters off Taiwan was slower than in Japanese waters. The increasing use of the Taiwanese seine in the northeastern waters off Taiwan has increased the catch and the proportion of jack mackerel, but the utilized jack mackerel are mainly age-0 (39%) and age-1 (38%), which are mostly at the immature stage. To conserve the resources of parent fish, it is necessary to implement fishing moratorium measures during their spawning period or to implement restriction of fishing gear and method, as well as limits on the total number of catches to reduce the mortality of spawning and young fish.

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